ACCESSIBILITY DISPARITY BETWEEN TRANSIT AND AUTOMOBILE: A STUDY OF ATLANTA AND SEATTLE

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ACCESSIBILITY DISPARITY BETWEEN TRANSIT AND AUTOMOBILE: A STUDY OF ATLANTA AND SEATTLE

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SUMMARY

This paper aims to study the disparity in accessibility between transit and automobiles, and to understand factors including traffic conditions, transit frequencies, and transit infrastructure that affect the accessibility gap and transit competitiveness. Trips between selected activity centers in Atlanta and Seattle were measured from 7 am to 10 pm to be used as two example cities. Google Application Program Interface (API) was used to estimate travel time and other parameters for each trip.

In total, 5472 trips in Atlanta and 8832 trips in Seattle were studied. To compare accessibility between the same origins and destinations by different modes, the ratio of travel time is used extensively, including transit access time and parking penalties. The results suggest the gap between transit and auto accessibility is smallest in morning and afternoon peak hours. Transit travel time and route circuitousness is reduced during peak hours while the automobile has significantly longer travel times during that period.

Standalone transit parameters in Atlanta are better than those in Seattle, but when compared to local automobile parameters, Seattle's transit proves more competitive against automobiles. High quality transit services are also distributed more consistently across the system in Seattle than in Atlanta. This paper demonstrates the importance of comparing transit parameters and system performance to other locally available modes and looking at the distribution of service qualities.

1. INTRODUCTION

1.1 Mobility and Accessibility

Mobility refers to the freedom of movement (*1*) and speed with which vehicles travel on roadways. Accessibility, however, adds traveler's perspective into the definition of mobility and expands its definition to the ability to "gain access to places" (*2*), and ease with which destinations can be reached from a given location (3). Accessibility annotates the practicality of reaching desired locations within an acceptable travel time and its definition emphasizes door to door access and accounts for the mode choice. This paper discusses and compares the accessibility achievable in Atlanta and Seattle via two dominant modes of transport in most cities: automobile and transit. Other modes of transport are equally important to the transportation system, but given the size and sprawling development patterns of most U.S. cities, other means of transport serve substantially fewer commute distance trips. Data availability on the less commonly used modes also restricts research on these modes. The focus of this paper is on door to door accessibility between selected locations using automobile and transit modes.

1.2 Measures of Accessibility

Measurements of transit accessibility are more useful when compared to other modes. For the general public and transit agencies, this competitive advantage forms the basis for a traveler's mode choice, ridership, and ultimately the market share of transit services. For the transit dependent population, difference in automobile and transit accessibility level is the source of social exclusions and disparity in work opportunities (*4*), and there are equity implications because transit serves as the equivalent of a "social safety net".

To measure and compare accessibility provided by automobile and transit modes, travel time, speed, and distance traversed, as well as temporal and spatial variation of these parameters are useful indicators. Travel time is the major determinant of accessibility as it is most directly experienced by users (*5*); speed mostly reflects traffic conditions; distance traversed is mainly a measurement of "out-of-direction" travel by transit. Variations in these parameters across time and space are critical in understanding the competitiveness of each mode, especially as the competitive advantage of automobile and transit changes constantly throughout the day.

1.3 Mode Competitiveness

Competitive advantages of automobile and transit are affected by many factors. In most cases, automobiles travel faster and provides better accessibility than transit. The gap in accessibility between automobiles and transit does not remain the same for all origin-destination pairs (ODs) or throughout the day; the comparative advantage of automobile over transit shifts depending on circumstances. Demand for travel varies throughout the day and transit operators adjust their service frequencies accordingly to meet the changing demand; roadway speeds are imped by congestion during peak hours; route and travel distances between the same set of ODs are different in response to changes in traffic conditions; locations in urban centers have a denser transit network and less parking availability which discourages auto use. The above factors cause constant changes in the competitiveness of transit, to the extent that using transit over automobile would be preferable in many instances. Understanding interactions between these factors and the underlying mechanisms responsible for the spatial and temporal variations in modal competitiveness would be helpful to plan improvements in transit service.

1.4 Data Sources

In order to study and compare transit and automobile accessibility at the system level, reliable data sources are needed to construct a travel time model that best replicates actual travel experience. The Google API is an ideal source for establishing comparison between automobile trips and transit trips. The Google API uses historical data for minute to minute automobile travel time estimates for the shortest route choice, however, the downside is that Google does not account for parking time penalties. Travel time adjustments to compensate for parking have to be added from data based on parking maps from city governments and other studies on parking occupancy rates. Transit travel times from the Google API are reasonably accurate, as its estimates are based on General Transit Feed Specification (GTFS) published by transit agencies that contain schedule information; traveler waiting and walking time are also included. Using the above data sources, separate travel time models for transit and automobiles measure transit accessibility in comparison to that of the local automobiles, and help shed light on mode competitiveness.

2. LITERATURE REVIEW

2.1 Definition of Accessibility

Two types of accessibility have been discussed in the literature: person accessibility and place accessibility (*3*). Person accessibility describes places accessible to a person and it depends on mode availability, income, and time budget of that specific person (*3)*. Person accessibility is a concern for social justice but not the main focus of this study. Place accessibility describes characteristics of places and accessibility of those places to people using different modes (*3*). Place accessibility mostly depends on the locations and the transportation system linking these places, and is the focus of study in this paper. Most of the literature regarding accessibility uses travel time as a main indicator, because time is closer to traveler's actual experience than distance (*5*).

2.2 Measures of Accessibility

Accessibility via public transit has been measured independently from other modes. The LAUTAI indexing model was developed to measure levels of accessibility to basic community services, and it provides a grid level origin-based accessibility index by measuring transit travel times and walking distances (*6*). Transit travel times of this model were estimated with scheduled time tables; however, walking distances in this model were derived through a household travel survey. The practice of using distance estimates by respondents in household travel surveys often lacks accuracy, and distances of shorter walking trips in particular are often found to be underreported (*7*). Another study in New Zealand used similar methods to generate a destination-based transit accessibility index. A local transport authority provided that study with actual transit operating data to estimate transit travel times; walking times were calculated with road network and assumptions on walking speeds. Travelers at all bus stops were assumed to have the same waiting time (*8*).

Several researches have also measured transit performance in comparison to automobiles. A local transit-auto travel time analysis by the City of Bellevue's Department of Transportation based on Google Maps found that the ratio of travel time via transit and automobiles varies significantly at different times of the day, and at different levels of congestion. Travel time was estimated at route level and factors including congestion, infrequent service and out-of-direction travel were identified as major causes impacting transit competitiveness (*9*). Three models with different levels of details regarding parking, congestion and transit schedule was used by Salonen and Toivonen (*10)* to analyze accessibility disparity between transit and automobiles. In the three models, the study area was divided into rectangular grids and the number of cells accessible from public libraries used as accessibility measures and the road class was used to account for travel speeds. The research found transit closer to downtown area has lower transit/auto travel time ratio. Benenson et al. (*11*) studied transit and automobile service gaps based on travel time thresholds and argued that previous researches lack consideration for transit access time, and that transit would have lower accessibility when door to door access is considered in the analysis.

Transit performance is important because of its relationship to ridership, and its equity implications for both choice and dependent riders (*12*). Research has indicated that transit has been inadequate in providing accessibility. Transit dependent populations have less access to jobs, social occasions, and healthy food due to limited transit coverage and the temporal accessibility imposed by transit schedules, service spans further limit the percentage of day those vulnerable populations can reach destinations via transit (*4*). Transit service has been measured independently by various agencies in different ways, among these, common measures include spatial coverages such as air distances like the 0.25-mile buffer around bus stops (*12*), and actual walking distance used by San Diego and California (*13*). Availability measures include transit frequency, capacity, service span (*12*), and service gap measures to identify where transit service is lacking (*14*).

Google API and GTFS published by various agencies are frequently used by researchers to study accessibility. A study by Farber et al. used GTFS data to measure transit travel time from census blocks to the nearest supermarkets at different times of day in Cincinnati, Ohio and identified areas of "food deserts" for the transit dependent population (*4*); they found high degrees of variability in transit travel times at different times of day.

3. METHODOLOGY

3.1 Trips Between Activity Centers

This paper identifies 19 activity centers in Atlanta and 24 in Seattle to construct OD matrices for trips between these locations to study travel time, speed, and distance traversed between these centers as well as temporal variation of these measures. Activity centers selected are each within a quarter mile of existing transit stops and are characterized typically by higher land use density with a mixture of land use types, thus making these locations common trip starting or ending points. The decision to study trips between activity centers has been informed by the literature: observations on household behavior found that “household activity patterns tend to be oriented toward regional centers” (*15*) with higher land use and population density, especially for the transit dependent population. Previous studies have observed that these populations have “activity patterns oriented along major transport routes, and toward regional centers” (*15*). Another reason for this paper to be anchored on trips between activity centers instead of commute trips is to avoid over emphasizing the importance of commute trips, since commute trips account for about 23.1% of person vehicle trips and 33.5% of person transit trips. (*16*).

By studying transit and auto trips between activity centers, this paper attempts to shed some light on differences between the two modes. Activity centers were selected based on land use density, landmarks, and regional centers; A list of transportation derived common place names from Seattle Department of Transportation and a digitized map of activity centers developed by Atlanta Regional Commission were used as references during the selection of activity centers for this study. Addresses of these activity centers were entered into Google Maps and their coordinates were then used in the Google API to estimate travel related parameters between activity centers. Geographical locations of these activity centers are shown in figure 3.1 and a full list and descriptions of these activity centers are provided in appendix A.

Atlanta Seattle

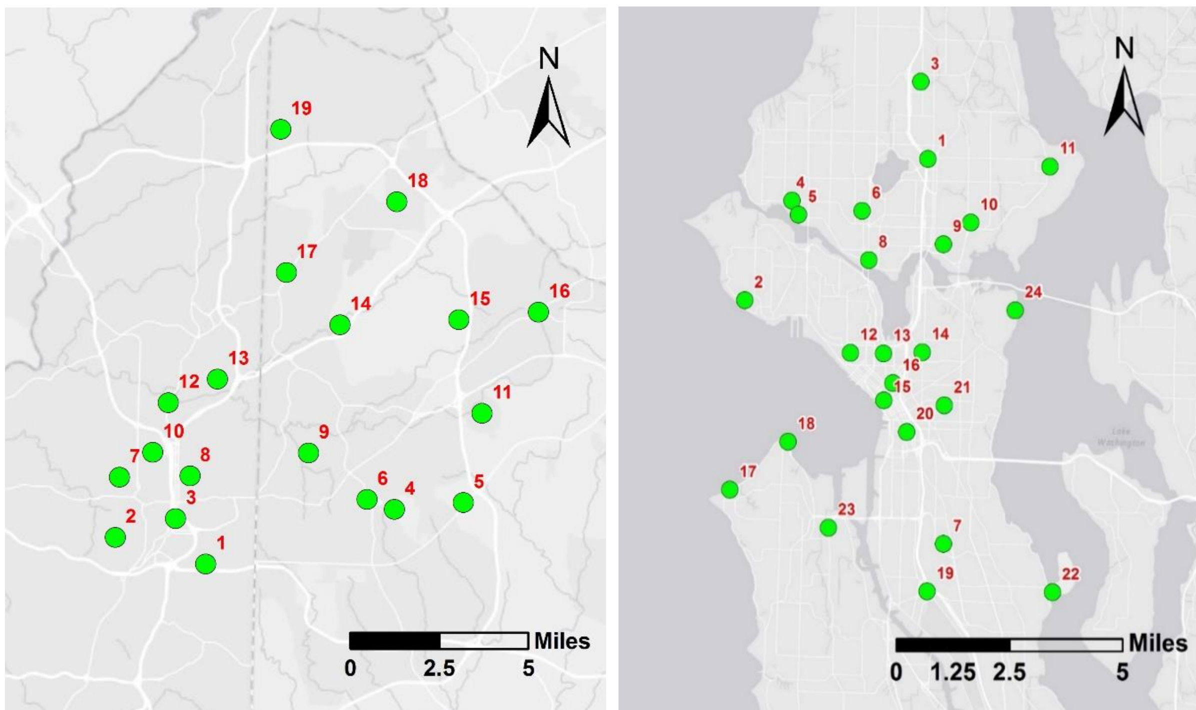

Figure 3.1 Selected Activity Centers in Atlanta and Seattle

3.2 Parking Time Penalty

Time spent looking for parking and then walking from the parking lot to the actual destination constitutes a significant portion of the total travel time of the automobile mode in urban areas, especially for short distance trips. This aspect of motorized travel has often been unaccounted for in other researches mostly due to difficulties in obtaining the data, and even when specific data have been collected, variations between different sites often limit their use. For example, a study in Los Angeles observed the average time spent cruising and looking for an on street parking spot was 3.3 minutes (*17*), but this data was site-specific for a busy street and cannot be applied to other locations. This example nonetheless showed that automobile travel time can be more volatile in the real world than in mathematical models, because not every aspect of parking facilities can be determined with certainty. In this paper, parking time penalty is composed of time searching for a parking spot, and time walking from parking lot to the actual destination. Search time for parking is estimated using the vacancy rate of parking facilities adjacent to the destination, and walking time is calculated as a function of walking speed and average distance of parking lots near destinations that are within an acceptable walking distance threshold.

To estimate time spent by travelers looking for a parking space, this paper uses a model developed by Belloche (*18*) which had been calibrated with actual survey data. Specifically, this model assumes an exponential form and takes into account occupancy rates at parking facilities. The equation (1) describes the relationship between parking search time and occupancy rate. In which α and β are coefficients calibrated through a survey (*18*) and R_{occ} is occupancy rate of the parking lot. Coefficients α and β are assumed to be 0.110 and 8.586 respectively, according to Belloche (*18*). Figure 3.2 shows parking search time in relation to occupancy rate of parking facilities. This model for parking search time is intuitively reasonable in the shape of its plotted function: search times are negligible at low occupancy rates, then increase exponentially as parking lots near their full capacities.

$$T_{search\ for\ parking} = \alpha \times e^{-\beta \times R_{occ}} \tag{1}$$

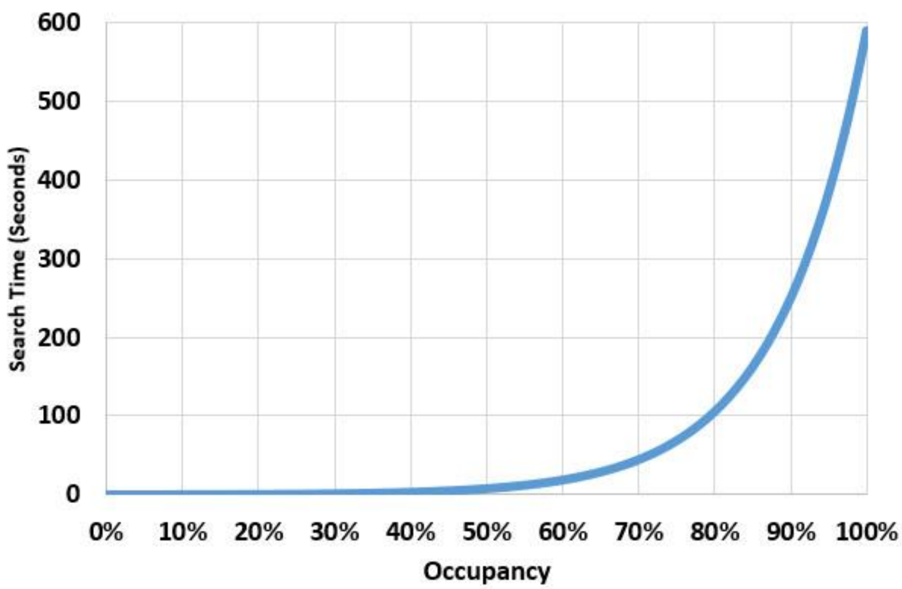

Figure 3.2 Search Time for Parking in Relation to Occupancy Rate

Walking from parking lots to destinations is another aspect of using automobiles. Because survey respondents typically have difficulty accurately estimating time and distance, survey data would most likely be unreliable for this purpose (*7*). Looking at the design aspect of parking facilities would offer a better chance of getting accurate estimates of acceptable walking distance threshold. According to the National Parking Association, parking facility designers typically limit walking distance to within 300 to 600 feet for retail customers, and longer distances would be used for workplace and special event parking (*19*). Though these numbers do not match exactly each parking facility, they provide a reference for better estimation. For the purpose of estimating travel time in this paper, a 500 feet threshold distance is assumed to be acceptable and parking lots within that threshold distance will be used by travelers. This 500 feet threshold distance is then used to search for available parking lots in the vicinity of each trip destination. The average distance of these parking lots within the threshold distance is used as walking distance for the last stage of automobiles trips. Parking lot data collected by city governments are rarely comprehensive and some areas have no parking lots on record. In these cases, “mean substitution” is used to replace missing occupancy rates with the city’s averages. Walking time "T_{walk}" is then derived through dividing distance by walking speed.

It should be noted that due to variation in parking facilities and individual differences, these calculated parking penalties are rough estimates. Since “All models are wrong” (*20*), the travel time model used in this paper attempts to provide a useful estimation of accessibility for different modes, and make it better than not accounting at all for details such as parking and walking for access. Parking time penalties depend on characteristics of parking facilities near the destination of each auto trip. In Atlanta, parking penalties average 88 seconds and the numbers range from 76 to from 101 seconds; most of the penalties were incurred by walking from the parking lots to the destinations as the time spent searching for parking are low for most of the locations due to higher parking vacancy rates in Atlanta. On average, 156 seconds are added for activity centers in Seattle and the penalties range from 97 to 405 seconds; times spent looking for vacant parking spaces are significantly longer in Seattle than in Atlanta.

3.3 Travel Time Estimates

Transit and automobile levels of services are defined in many ways and affected by numerous factors, major determinants of service quality include transit service frequency, traffic condition, comfort, and walking time. This paper uses the ratio of door to door travel time between transit and automobile as a benchmark to measure the comparative level of service provided by transit and automobiles. For the trip to reflect normal travel experience and facilitate comparison between the two cities, all estimates are made on a Wednesday, January 11, 2017 from 7am to 10pm.

Base travel time between activity centers was estimated through feeding departure time, origin and destination coordinates into the Google API. Through Google's Distance Matrix API, researchers can request travel distance and estimated travel time in traffic with inputs including origin, destination, travel mode, date and time of departure. Google doesn't disclose how they make predictions and claims travel time estimates are "best guesses" based on historical traffic conditions (21). For the auto mode, the API output includes only the driving part of the actual trip and parking time penalties are added to account for the missing parts. For the transit mode, the API output is based on GTFS from local transit operators and has accounted for walking time at both ends of the trip, and any transfers necessary during the trip. It is assumed that trips between activity centers are made either by auto or by transit, and the travelers do not combine modes for the trip.

Adjustments to the initial API outputs are made to improve estimate accuracy of the auto mode. A trip made by auto is modelled to have three sequenced stages. The first stage is driving, the trip starts with the traveler in the vehicle departing from the origin site and driving via the route with shortest driving time at the time of departure until it arrives at the destination activity center. This part of travel time is obtained from the Google API and vehicle driving speed takes into account traffic conditions and potential delays at that time. It is worth noting that vehicle driving speed is not restricted by posted speed limits because the estimates are based on historical data. The second stage starts when the vehicle arrives at the destination, and ends after the traveler finds a parking spot and parks the vehicle, which in theory could take from 0 to 9 minutes depending on occupancy rate of adjacent parking facilities. In the third stage, the traveler exits the vehicle and walks as a pedestrian from the parking lot to the actual destination. The composition of an automobile trip is described by equation (2).

$$T_{automobile} = T_{drive} + T_{search\ for\ parking} + T_{walk} \tag{2}$$

Transit trips include three stages. The traveler starts the trip as a pedestrian and the first stage is walking to access the transit stop. The second stage consists of any combination of times using the transit system, including initial waiting time, time on transit vehicles, waiting for connecting transit services, and walking between transfers. The third stage of a transit trip is egressing from the transit stop and walking to the actual destination. The whole transit travel time has been estimated with reasonable accuracy by API output and the detailed trip composition of a transit trip is shown in equation (3).

$$T_{transit} = T_{access} + T_{in\ transit} + T_{egress} \tag{3}$$

The approach of measuring the ratio of travel time has several benefits not afforded by other conventional methods. Ratio of travel time reflects the real choice scenario faced by travelers when deciding which mode will get them to their desired destination faster. Ratio of travel time takes into account localized circumstances that facilitates cross comparison between different cities. It would be less costly for cities with light traffic conditions to build a transit system that appears great on standalone performance measures, while cities with heavy congestions need vastly higher investments to provide transit right of ways and other preferential treatments in order to achieve similar statistics. Under such circumstances, using local automobile as a benchmark for mode to mode comparison would be more effective.

The travel time model in this study is intended to measure and compare the level of accessibility achievable via the transit system with its local automobile competitor, assuming trips between selected ODs were to be made at certain times of the day. Components of transit and automobile travel times are designed to reflect this purpose; however, certain aspects in this model constructions might favor the auto mode. Starting point of automobile trips are set in a way that puts automobile travels in a more favorable position. Automobile trips are assumed to start with the driver already inside the vehicle, and parking time penalties are added only at the destination end of each trip. This assumption is made because of the difficulties in accurately estimating the amount of time needed for a traveler to access the vehicle, and because real trips have a variety of starting points that would be too subjective to define. In the transit travel time model, travelers are assumed to start the trip at the same time as he would be using the auto mode. This is sometimes not true because frequent transit users would often check the transit timetable before walking towards a transit stop. Attempts to account for this aspect of transit trips would be subjected to individual variations and make the estimated results less accurate. However, it should be noted that compared to trips made in real life, travel time estimations might be in favor of the automobiles.

4. MEASURES OF ACCESSIBILITY

Speed, travel time and delay are commonly used indicators for performance of traffic facilities (*2*) and are applicable for both auto and transit modes. In this paper, temporal variation of speed is used to represent traffic conditions, and to identify hours when travel demand peaks; travel time serves as the primary indicator of accessibility, and the ratio of transit/auto travel time compares level of accessibility provided by the two modes; delay is reflected in the variation of speed and travel time at different hours of the day; and route circuitousness of transit in comparison to automobile is included as an additional measure of transit service and accessibility it provides. The relationship between transit frequency and transit level of service is examined, in which transit frequency is defined as the number of transit vehicle arrivals at transit stops in the 10-minute period (5 minutes before and 5 minutes after) of the specific time point. The frequency measurement in this paper is not a conventional measure of how many buses or trains are dispatched from garages as from the transit operators' point of view, but a measure of how many buses or trains actually arrive at transit stops that are available for travelers, as from the users' perspective.

4.1 Accessibility Disparity and Mode Competitiveness

Disparity in accessibility between auto and transit is manifested by their difference in travel time between the same set of ODs. On average, transit trips in Atlanta takes 2.26 times the amount of travel time by auto. Transit trips in Seattle are more competitive against auto and it still takes 2.14 times the auto travel time. For the majority of trips, automobile has less travel time. In Atlanta, 3.47% of the trips take a shorter time by transit; and 2.67%

of transit trips are faster than auto in Seattle. These quality transit services are clustered at several locations. Downtown and the international district are locations where quality transit services are concentrated in Seattle; In Atlanta, quality transit services are close to heavy rail (MARTA) stations such as Lindbergh Center, Ashby, and downtown.

Accessibility of both transit and automobiles varies at different times of day, and congestion is responsible for a significant amount of this variation. When demand for travel approaches road capacity during peak hours, traffic flow becomes unstable and begins to slow down (*2*), people start to experience delays because less traffic can go through facilities and congestion occurs. In the case of Atlanta and Seattle, congestion is identified to peak at 8 am and 5 pm when automobiles have lower travel speeds than any other time of the day. Negative effects of congestion on travel are manifested by reduction in travel speeds. At the system level, the automobile has predominantly higher travel speed than transit. Although transit vehicles do not necessarily drive slower than the automobiles when in operation, they keep going through the cycle of decelerating, stopping for passengers and then accelerating again, which slows down the overall travel speed of the transit mode. Both automobile and transit mode display a typical pattern of reduced travel speeds during morning and afternoon peak hours when demand for travel reaches its highest point, as shown in figure 4.1. Automobile travel speeds at morning and afternoon peak hours in Seattle are reduced to between 73% to 82% of its travel speed at noon. Transit travel speed is less affected by changes in traffic conditions, although slight decreases in speeds are observed during peak hours. In Seattle, transit travel speed is at its lowest at 5 pm and the transit speed retains 96% of the speed at noon. Travel speed in Atlanta has the same pattern although average automobile and transit travel speeds are higher in Atlanta than in Seattle.

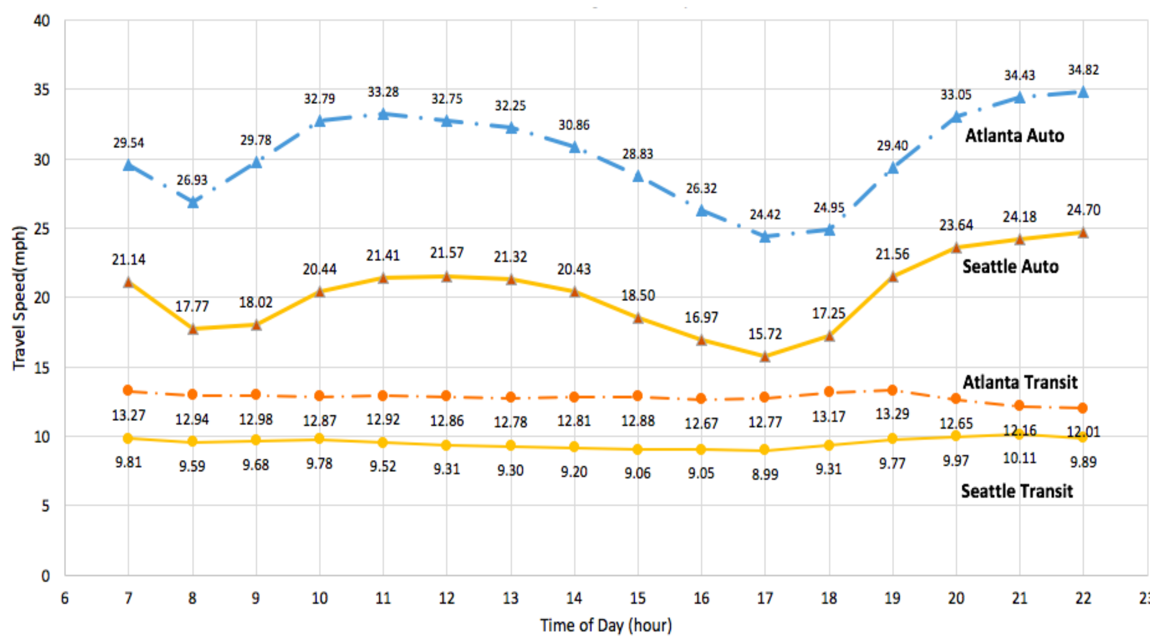

Figure 4.1 Auto and Transit Travel Speed Variations

Route choice between activity centers is also affected by changes in traffic conditions. As mentioned in the methodology section, trips are assumed to take the route with the shortest travel time; consequently, trips made at various times of day might have different routes and travel distances. Automobile trips react to congestion during peak hours by switching from busy highways and major arterials to local roads which provides less travel time and shorter travel distances (1% to 3% shorter than noon) because these local roads typically have less out-of-direction travel. Transit trips have different routes at different times of the day, and travel distances are shorter during peak hours, although this is more of a result of better and more frequent services available during peak hour than deteriorating traffic conditions. Transit trips in Atlanta made during peak hours are about

3% shorter on average than the same trips made at noon, and the number is 7% in the case of Seattle.

Slower travel speed in peak hours does not necessarily mean peak hour travel time for auto and transit mode are both extended. Travel time is a function of both travel distance and travel speed, when speed and distances are reduced at the same time, magnitude in these reductions determines the outcome. For the auto mode, shorter travel distance doesn't offset reductions in travel speeds. On average, auto trips made during peak hours take 19% to 37% longer time than trips made at noon. Transit trips during peak hours, on the other hand, have between 4% to 10% shorter travel time than trips made at noon.

The gap in accessibility between transit and auto diminishes in peak hours, and transit becomes more favorable in terms of travel time. This diminishing gap is manifested by three measures during peak hours:

- Reduction in transit/auto travel time ratio
- Less circuitous transit routes
- Transit becomes more reliable

The ratio of transit/auto travel time reduces most significantly during peak hours at 8 am and 5 pm in both cities. This is a combined result of increasing automobile travel time caused by congestion and reducing transit travel time due to more frequent services, and less circuitous routes. Both automobile and transit have shorter route distances during peak hours and reductions in transit route distances are more significant than that of the auto mode, as indicated in figure 4.2 by transit/auto distance ratio.

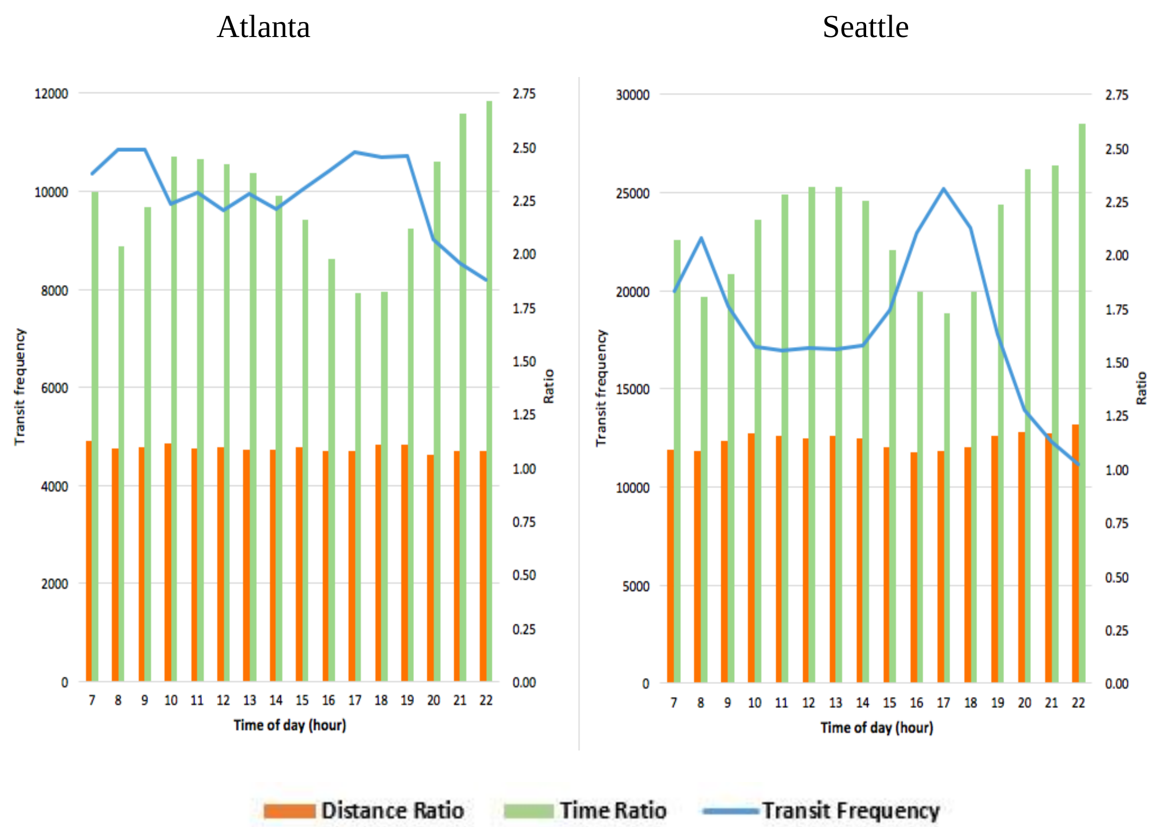

Figure 4.2 Ratio of Transit/Auto Travel Time and Distance by Time of the Day

The distribution of transit/auto travel time ratio is a measure of inequality in accessibility of auto and transit modes, and it offers a valuable glimpse into transit infrastructures beyond average system measurements. Shown in figure 4.3 are the distribution of travel time ratios for two peak hours (8 am and 5 pm) plotted in red against the distribution of every other off peak hours' travel time ratio, shown in green. The ratio of transit/automobile travel time appears to have a bell-shaped, normal-like distribution for each hour's statistics, with its shape skewed to the right. The two peak hour's distribution have a mean closer to "1" than the rest of hours, which means gap between travel time of the two modes becomes smaller during peak hours. The peak hours' travel time ratio distribution also appears to be more centered towards the mean and the distribution tend to spread out during off peak times. Standard deviations of this distribution during peak hours are 10% less in Atlanta and 40% less in Seattle than all day average values of each of the two cities. This shift in peak hours' time ratio distribution demonstrates how the transit competitiveness improves during that time period, and that the scale of improvement is system wide and not just for a few locations.

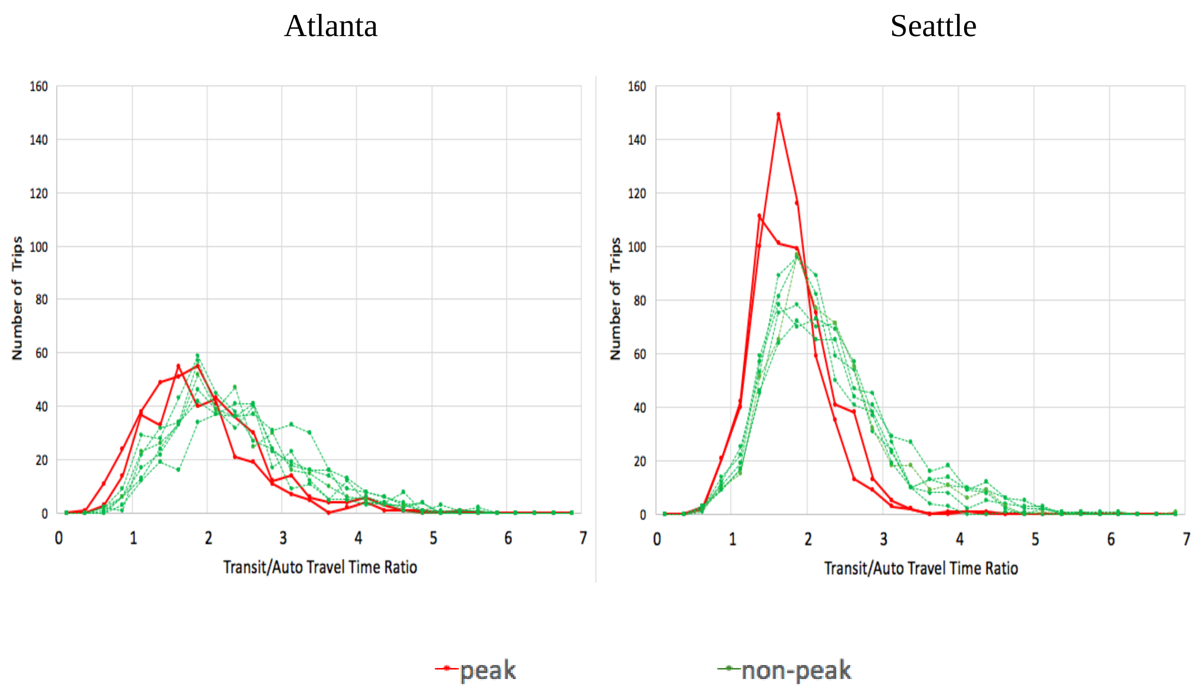

Figure 4.3 Distribution of Travel Time Ratio

Another aspect manifested in the distribution is the small proportion of transit trips that are faster than automobile over the same ODs (i.e. travel time ratio ≤1), and Atlanta has a bigger share in this portion in these quality transit services than in Seattle. In terms of the overall distribution of travel time ratio, however, Seattle's transit offers better transit competitiveness than in Atlanta. First and foremost, travel time ratios in Seattle are more centered around the average and have light "tails" over extreme values of travel time ratio, which means more consistent services across the system. There is also clearer differentiation between peak and off-peak services in Seattle than in Atlanta; the shift in travel time ratio distribution towards the left is clearly visible in the figure 4.3 and the average value in the bell-shaped distribution is significantly below “2”, which means transit users can expect to arrive at destinations within twice the amount of automobile travel time during peaks. In peak hours, 95 percent of trips in Seattle can reach their destinations within 2.7 times the travel time by automobile, and the 95-percentile travel time ratio is 3.3 in Atlanta during peak hours.

Transit provides better accessibility through congested time periods and in places with limited parking availability. An example can be found in downtown Seattle. Downtown Seattle has very competitive transit travel times, especially during rush hours and a great number of available transit services and bus stops are clustered around downtown. A 1.7-mile trip from the Art Museum in downtown Seattle to Broadway Market at Capitol Hill is faster by transit during most times of the day despite autos having higher travel speeds. This is mainly due to the short distance of the trip and limited parking availabilities at destination that added more than a minute as parking penalties. Atlanta’s heavy rail provides better transit accessibility through congested time periods using exclusive right-of-way. A 5.4-mile trip from Lindbergh to Civic Center in downtown takes about 12 minutes at 5 pm; the same trip would take 33 minutes by auto. The red and gold line operating on this segment of heavy rail provide a combined headway of 5 minutes at 5 pm, meaning expected waiting time per passenger is only 2.5 minutes. Even when parking penalties are removed for the auto mode, transit still has significantly shorter travel time.

Differences in transit infrastructure are responsible to a great extent for this difference in travel time ratio distribution between the two cities. Seattle has more transit vehicles and serves a smaller area than Atlanta, this gives transit operators more flexibility in responding to demand during peak hours by adding more services. Transit preferential treatments in Seattle, including exclusive transit lanes, transit signal priority and queue jump lanes (*22*) are another reason for better transit-auto competitiveness in travel time. These preferential treatments reduce gaps between travel time differences between the two modes.

4.2 Implications of Transit Frequency

Transit service frequency in this paper is measured by the number of transit vehicle arrivals at stops. Transit operators in both Atlanta and Seattle increase service frequencies to meet surging demand for travel during peak hours. A noticeable difference between the two cities is in the duration of peak transit services: Atlanta transit's peak frequency is increased slightly and kept running for several hours at its peak hour service frequency; while Seattle's transit frequency drops immediately after reaching its peaks at 8 am and 5 pm (as shown in figure 4.2). Using frequency at noon as a benchmark, Atlanta's service frequency increases by 13% for the time period between 8 am and 9 am in the morning and between 5 pm and 7 pm in the afternoon; Seattle's transit service increases by 33% at 8 am and 48% at 5 pm. Seattle's transit agency appears to have greater resources and adopted a more dynamic transit schedule that differentiates morning and afternoon peak hour service frequencies. This increase in service frequency improves transit travel time, reliability of service and travel speed (*22*) (*23*). Improvements in transit travel time and reliability are confirmed by our data in this study. The effect of frequency on transit travel speed cannot be verified because both increase in service frequency and deterioration in road speeds occur at the same time during rush hours. However, it is obvious that improvements in transit running speed, if any, cannot offset the effect of congestion. Additionally, this study finds having more frequent services significantly reduces route circuitousness for the transit mode. It should be noted that numbers for transit frequency shall be viewed only as a relative value and not be used for comparison between different cities.

Transit travel speed is affected by many factors including service frequency, passenger service time, and road conditions; and transit preferential treatments and longer stop spacing often result in higher transit running speeds (*23*). Among these factors, interactions between traffic conditions and transit frequency have a great bearing on travel speed outcomes, and are directly observable from statistics. Transit service frequencies affect travel speeds in many ways. On the one hand, the major effects of higher service frequency are the reduction in waiting time at stations. Dwell times are also reduced, which means the transit can run faster when in operation. On the other hand, increases in service frequencies for well-designed transit systems often coincides with the time when peak travel demand occurs (as in the case of Atlanta and Seattle), and traffic conditions are at their worst; as a result, transit running speeds are adversely affected. These two factors counteract each other and depending on the specific transit system layout in different cities, the combined effect can be entirely opposite. As shown in 4.4, Atlanta shows an increased transit travel speed with higher service frequency, and in Seattle, transit travel speed is reduced when traffic conditions deteriorate and more services are available. However, reductions in transit travel speed do not necessarily mean travel time between places would take longer by transit, because when service frequencies are increased, more route options enable travelers to take shorter and less circuitous routes than off peak hours; the eventual travel time would depend on both travel speed and route distance.

Increases in Atlanta transit's travel speed with more services suggests the inadequacy of current transit service in Atlanta. The effect of having less waiting time at stops outweighed speed reductions of transit vehicles during peak hours, showing that there is ample room for transit improvements by simply providing more service in Atlanta. In Seattle, however, adding additional service is not increasing travel speed for transit users. This is not to say increasing transit service during peak hours is not worth it, because if the frequency is not increased to counterbalance congestion, travel speed might have further decreased.

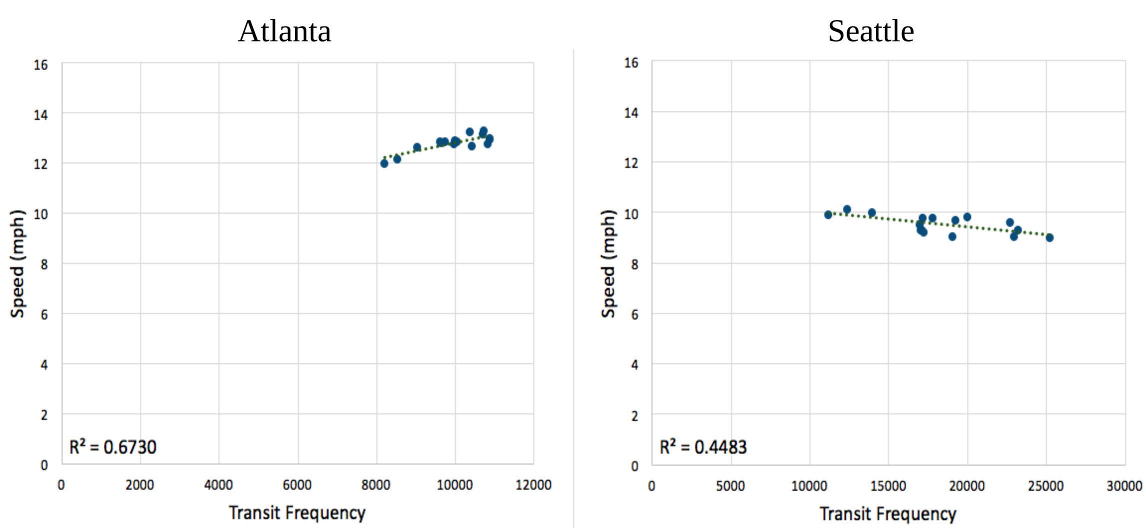

Figure 4.4 Transit Travel Speed and Service Frequency

Higher transit frequency is associated with less transit route circuitousness. Both automobile and transit travel distances shorten during peak hours, but for different reasons and vary in magnitude. For automobiles, travelers avoid congested highways and major roads and switch to local roads during peak hours, reducing travel distance, but its reduction in distance is small in effect. For transit, however, reduction in route distance is mostly a result of more frequent service available that allows more direct travel routes.

Transit travel distance and the ratio of transit/auto travel distance are plotted in figure 4.5 in relation to transit service frequency. In Seattle, the trend of increasing service frequency and decreasing transit route distance as well as the ratio of transit/auto travel distance can be well described with a linear function. When transit is operating at its highest frequency of the day, transit travel distance in Seattle came very close to that of the auto mode, to the point that they almost became equal. Thus, it might be a tempting idea to predict the critical value in transit frequency that brings ratio of transit/auto travel distance equal to one, which is very difficult in reality. Transit routes are designed to connect multiple locations and not to provide direct access between any two of these locations, consequently travelers using transit would have to travel on routes more circuitous than automobile with more out-of-direction travel and transfers; walking to access stops at both ends of the transit trip also adds to the travel distance.

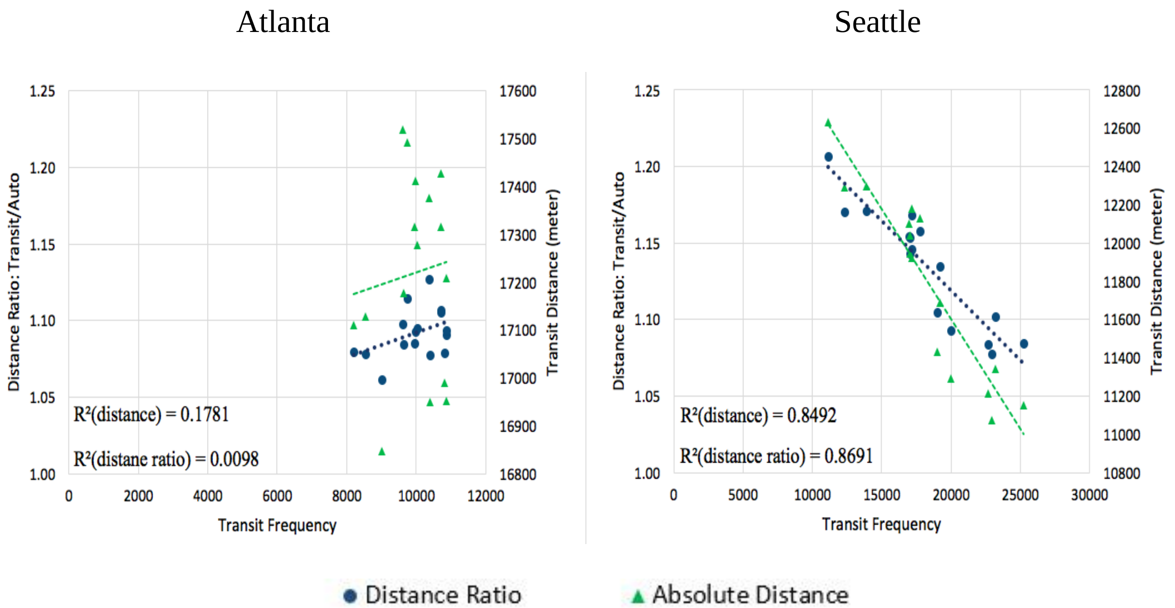

Figure 4.5 Average Transit/Auto Travel Distance Ratio and Average Transit Travel Distance

The increase in service frequency improves transit travel time in both Atlanta and Seattle. The relationship between transit frequency, mean transit travel time and ratio of transit/auto travel time for every hour are plotted in figure 4.6. The increase in transit service frequency and reduction in transit/auto travel time ratio as well as transit travel time can be described with linear functions. Transit travel time is affected in two ways by frequency. On the one hand, more frequent services reduce waiting time at transit stops. On the other hand, it reduces route circuitousness and thus transit travel distances are reduced.

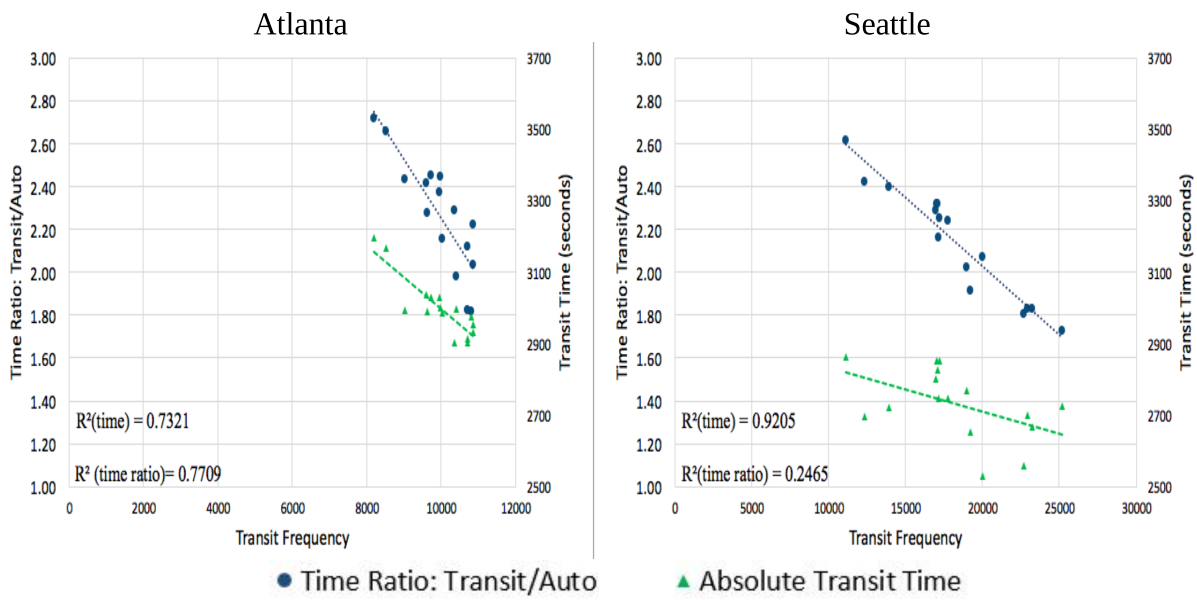

Figure 4.6 Transit Travel Time and Service Frequency

4.3 Mode Reliability

Reliability is an essential part of mode competitiveness. Reliability affects how much extra time travelers need to schedule in addition to the travel time under normal circumstances. For transit, reliability ensures timely arrival at destinations without an unreasonable amount of waiting time and delays that affect service quality. Unreliable and frequent transit lines can cause vehicle bunching (*12*), and increase operating cost for transit operators. For automobiles, adverse traffic conditions are the main cause of reliability problems. In practice, reliability can be measured with variances in the travel time. To enable effective comparison between automobile and transit reliability when the two modes have different mean travel times, coefficient of variation (CV, also known as relative standard deviation) is used in place of standard deviation.

Transit travel times are more reliable than automobile travel times. Despite slower travel speeds of transit services, transit travel times are more predictable with less variation than the auto mode. This applies to the majority of trips between our activity centers. There is 31% greater variation in auto travel times than transit in Seattle, and the number is 66% in Atlanta. Travel time reliabilities of the two modes come very close for downtown activity centers, and in downtown Seattle, automobile has more consistent travel times than transit.

Automobile travel times tend to be less reliable at the outer edges of the city. Origin based travel times from locations far from city centers have drastically longer travel times during peak hours than the rest of the day; and coefficients of variations in travel time at these locations can be twice as much as in other places. It might be argued that these activity centers have longer travel distances to other places due to their outlying locations, and consequently variations in travel time are more likely to accumulate and result in higher CVs in overall travel time. This is not true because transit trips between the same locations experience comparable or longer travel distances than auto, but have travel times dispersions that are not different from transit services at other places. Obviously over the same travel distance, auto travel times are more susceptible to traffic conditions than transit. This is due to many reason, including: (a) Automobiles are faster and thus have more margin for fluctuations, and (b) Transit exclusive right-of-way over some segments insulates transit services from being affected by traffic.

5. A FEW CAVEATS

It should be noted that in developing trip models, some assumptions were made and some desired data was not available or was less accurate than desired. Though these assumptions, data availability issues, and data accuracy issues are not significant enough to affect conclusions made in this paper, for the benefit of future research, the issues are explained here. First, the parking penalty introduced, especially in downtown areas, accounted for a significant difference in transit's competitiveness. It is worth noting that parking occupancy rates used in this study are daily averages due to limited data availability. However, parking availability varies at different times of the day and between seasons, therefore using average values could lead to less accurate estimates of parking time penalties.

Estimates of travel times presented here have lower accuracy under some circumstances. Walking trips estimated in the Google API output might vary from the choice by actual travelers because it is assumed that travelers would abide by traffic rules and would not make any unlawful crossings. Therefore, some shortcuts accessible only by pedestrians are not present in the map network Google currently uses. Thus, it is possible for travelers to have shorter walking distances than that reported by API outputs. When the traveler uses a metro station instead of a bus stop, time spent walking through the facility cannot be neglected as in the case of small bus stops, however, this portion of travel time is not included in the API output. Thus, when a traveler uses the metro system, there is a small but not negligible proportion of travel time not accounted for. The travel time estimations in this study does not capture the individual variations such as timing transit trips according schedules. Starting points of trips are also set in a way that could sometimes favor automobile trips.

6. CONCLUSIONS

This paper analyzes trips between selected activity centers and provides extensive analysis of the ratio of travel time as a token of mode competitiveness. Using ratio to other modes instead of absolute numbers accounts for localized conditions and facilitates comparison with other places. Seattle has more congested roads than in Atlanta and has lower transit and automobile travel speeds. This is partially due to extensive water bodies in Seattle that restrict the development of its road network. Transit in Seattle has greater resources in transit vehicles and preferential infrastructure (22), and is more competitive against automobiles than transit in Atlanta. Higher transit frequencies in Seattle reduce route circuitousness but do not achieve higher travel speeds during peak hours because their effect is outweighed by congestion. Atlanta improved its transit travel speed with more services during peak hours.

Significant gaps exist between accessibility by transit and automobile at activity centers selected for study in Atlanta and Seattle. At the system level, the same trips by transit take more than twice the amount of travel time needed by automobiles. This disparity in accessibility is reduced during peak hours as a result of more frequent transit services and congestion that impacts automobile speeds more than transit, to the extent that travelers in both Atlanta and Seattle have expected transit travel times reduced to within twice of that of the auto mode. Transit trips involve longer distances than auto due to out-of-direction travels, and this route circuitousness is also reduced during peak hours when more frequent transit services are available.

Transit competitiveness can be improved in many ways for various times, different locations, and against other modes. Transit is more competitive in peak hours when its travel time decreases while other modes incur longer travel times. Frequent services during that period reduce out of vehicle waiting time and improve transit satisfaction. Transit is more competitive in urban centers where limited parking availability adds time searching for parking and walking from parking lots, therefore the effect of parking penalties is more acute for short trips. Transit travel times are longer but more reliable than automobiles especially for long distance trips. Lack of variations in transit travel times at different times of day make transit travel time more predictable and do not require travelers to schedule extra time in addition to normal travel times to ensure timely arrivals.

Exclusive right-of-way is found to be the most important element for transit to be competitive. When parking penalties were removed for the automobiles, exclusive transit right-of-way, and frequent service frequencies are common characteristics shared by OD pairs with faster transit service than automobiles. In Atlanta, locations near heavy rail have very competitive transit services. In Seattle, BRT and light rail routinely outrun automobiles over some short distance trips in downtown area. Transit incurs more travel time penalties than automobiles through circuitous routes, frequent stops, and transfers, etc. Among other preferential treatments, exclusive right-of-way can be the only edge held by transit to bypass traffic and be competitive against automobiles.

APPENDIX A. DESCRIPTION OF ACTIVITY CENTERS

Table A1. Seattle Activity Centers

Number	Activity Center	Coordinate	Address
1	Rainbow Point	47.682379, -122.320104	631 NE BANNER PL
2	Eastmount Place	47.637689, -122.405567	2201 Westmont Way W
3	Northgate Mall	47.706238, -122.324095	401 NE Northgate Way
4	Majestic Bay Theaters	47.668704, -122.384133	2044 NW Market St
5	Ballard Loft	47.664459, -122.380930	5105 Ballard Ave NW
6	Zoo South Gate	47.666005, -122.350779	750 N 50th St
7	VA Hospital	47.563709, -122.309372	1660 S Columbian Way
8	Fremont Troll	47.650913, -122.347196	3468 Aurora Ave N
9	University of Washington	47.656197, -122.312033	4045 15th Ave NE
10	University Village	47.663064, -122.299243	2623 NE University Village
11	Magnuson Community Center	47.680815, -122.262250	7110 62nd Ave NE
12	Key Arena	47.622107, -122.355099	305 Harrison St
13	Amazon Brazil Building	47.622093, -122.339344	400 9th Ave N
14	Broadway Market Capitol Hill	47.622762, -122.321128	401 Broadway E
15	Seattle Art Museum	47.607698, -122.338892	1300 1st Ave
16	Pacific Place	47.613039, -122.334751	600 Pine St
17	Alki Beach Park	47.579101, -122.410872	1702 Alki Ave SW
18	Harbor Eye	47.594302, -122.383813	Alki Trail
19	Rainier Glass Studio	47.548991, -122.316742	6006 12th Ave S
20	International District	47.598094, -122.327795	505 5th Ave S
21	Swedish Cherry Hill Campus	47.606489, -122.310263	500 17th Ave
22	Seward Park	47.549473, -122.257447	5900 LakeWashington Blvd S
23	Cap Food Services	47.568043, -122.363893	4025 Delridge Way SW

24	Madison Park Beach	47.636226, -122.277487	4235 E Madison St

Table A2. Atlanta Activity Centers

Number	Activity Center	Coordinate	Address
1	City Space Town Homes	33.7461, -84.3733	307 Cherokee Ave SE
2	Ashby	33.7563, -84.4176	47 Joseph E Lowery Blvd NW
3	Civic Center	33.7646, -84.3885	400 Ivan Allen Jr Blvd NW
4	Avondale	33.7703, -84.2819	198 Sams St
5	Kensington	33.7737, -84.2484	4246 Memorial Dr
6	Decatur	33.7741, -84.2954	400 Church St
7	Upper Westside	33.7812, -84.4163	820 West Marietta St NW
8	Midtown	33.7824, -84.3819	132 10th St NE
9	Emory University	33.7928, -84.3244	404 Dickey Dr
10	Atlantic Station	33.7917, -84.4003	361 17th St NW
11	Clarkston	33.8106, -84.2402	1092 Vaughan St
12	Buckhead South	33.8123, -84.3933	2111 Peachtree Rd NE
13	Lindbergh Center	33.8225, -84.3695	541 Main St NE
14	Century Center	33.846, -84.3104	1975 Century Blvd NE
15	Macy’s	33.849, -84.2524	4800 Briarcliff Rd NE
16	Old Trucker Mill	33.8528, -84.2136	4290 Railroad Ave
17	Brookhaven	33.867, -84.3371	4234 Peachtree Rd NE
18	Doraville	33.8971, -84.2838	5280 Buford Hwy NE
19	Perimeter Mall	33.9261, -84.3413	4400 Ashford Dunwoody Rd

APPENDIX B. HOURLY DISTRIBUTION OF TRANSIT/AUTO TRAVEL TIME RATIO

Table B1. Hourly Distribution of Transit/Auto Travel Time Ratio in Atlanta without Parking Penalties

Band 1: Atlanta		700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200
0.000	0.250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.250	0.500	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
0.500	0.750	1	2	0	0	0	0	0	0	2	3	8	7	1	0	0	0
0.750	1.000	1	7	7	3	2	4	5	5	5	13	17	15	8	3	2	2
1.000	1.250	11	33	12	10	11	10	12	12	22	26	36	32	19	11	7	6
1.250	1.500	29	34	34	21	20	22	18	29	25	31	40	42	27	21	18	16
1.500	1.750	31	41	28	31	29	30	34	31	36	49	48	62	41	27	11	12
1.750	2.000	44	49	49	20	27	30	33	38	41	45	57	41	39	37	25	24
2.000	2.250	48	38	34	43	40	39	43	43	44	46	43	45	52	30	28	34
2.250	2.500	30	34	45	40	42	42	39	43	39	40	31	34	44	41	38	39
2.500	2.750	37	33	34	31	35	29	38	34	33	25	13	19	28	36	32	32
2.750	3.000	25	16	26	43	29	37	30	21	31	14	15	14	20	29	36	30
3.000	3.250	23	15	21	21	23	19	21	23	23	16	10	9	22	31	28	23
3.250	3.500	16	13	12	11	24	20	16	19	9	9	6	6	11	19	32	30
3.500	3.750	11	7	12	21	14	16	13	15	7	5	8	6	10	8	22	27
3.750	4.000	5	4	9	12	12	13	9	8	8	8	0	0	4	15	20	10
4.000	4.250	10	1	3	8	7	7	2	4	5	3	1	1	4	10	9	10
4.250	4.500	4	5	5	7	7	4	8	7	4	4	3	3	7	7	13	14
4.500	4.750	10	7	3	5	6	5	4	3	4	1	2	3	2	2	3	14
4.750	5.000	0	1	5	7	9	8	7	3	3	1	0	0	2	6	9	5
5.000	5.250	2	0	2	5	2	2	5	3	1	0	0	1	0	2	2	2
5.250	5.500	3	1	0	1	1	1	4	1	0	1	3	1	1	2	2	2
5.500	5.750	0	0	0	0	2	3	0	0	0	1	0	0	0	3	2	4
5.750	6.000	1	1	0	1	0	0	1	0	0	0	0	0	0	1	1	2
6.000	6.250	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	2
6.250	6.500	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1
6.500	6.750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.750	7.000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table B2. Hourly Distribution of Transit/Auto Travel Time Ratio in Atlanta with Parking Penalties

Band 2: Atlanta		700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200
0.000	0.250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.250	0.500	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
0.500	0.750	2	3	1	0	0	1	1	2	3	4	11	8	2	0	0	0
0.750	1.000	1	14	7	6	6	6	6	6	7	20	24	25	9	6	3	3
1.000	1.250	22	37	28	13	12	17	21	23	32	26	38	32	29	18	12	12
1.250	1.500	32	33	29	24	26	22	23	26	23	40	49	56	28	23	19	19
1.500	1.750	34	55	35	34	28	33	29	33	45	54	51	55	43	33	16	12
1.750	2.000	57	40	53	42	49	46	48	52	48	47	55	54	59	41	34	38
2.000	2.250	39	43	39	37	40	39	38	39	45	48	41	37	45	38	37	39
2.250	2.500	32	36	45	41	42	36	48	47	35	34	21	22	38	40	36	35
2.500	2.750	40	30	32	41	29	41	38	25	36	19	19	22	27	40	37	35
2.750	3.000	17	12	18	24	34	23	23	30	25	15	11	8	24	25	31	24
3.000	3.250	23	14	14	18	15	19	16	16	11	10	7	11	9	20	33	35
3.250	3.500	12	6	17	16	20	16	13	15	8	9	5	2	11	12	30	22
3.500	3.750	5	4	6	14	11	16	9	10	12	7	0	1	5	17	16	19
3.750	4.000	12	4	8	9	9	5	5	6	2	2	2	1	5	7	13	14
4.000	4.250	4	6	2	8	5	6	5	5	6	3	4	5	3	7	8	10
4.250	4.500	4	3	2	6	7	4	8	3	2	1	1	1	4	7	6	9
4.500	4.750	2	1	5	3	7	8	6	3	2	1	1	0	1	2	4	4
4.750	5.000	4	0	0	4	0	1	3	1	0	0	1	1	0	4	1	3
5.000	5.250	0	0	0	0	2	1	1	0	0	1	0	0	0	1	3	5
5.250	5.500	0	1	1	1	0	1	1	0	0	0	0	0	0	0	1	2
5.500	5.750	0	0	0	1	0	1	0	0	0	0	0	0	0	0	2	1
5.750	6.000	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
6.000	6.250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.250	6.500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
6.500	6.750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.750	7.000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table B3. Hourly Distribution of Transit/Auto Travel Time Ratio in Seattle without Parking Penalties

Band 1:	Seattle	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200
0.000	0.250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.250	0.500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.500	0.750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.750	1.000	0	3	6	2	2	1	2	2	2	3	6	4	2	2	2	0
1.000	1.250	6	20	15	7	5	7	4	5	8	20	23	15	9	4	3	4
1.250	1.500	21	46	42	26	18	11	14	14	24	38	53	44	17	14	15	8
1.500	1.750	45	102	82	47	33	37	37	41	51	103	126	88	40	26	28	31
1.750	2.000	88	120	105	74	67	65	65	59	108	121	129	118	70	66	59	52
2.000	2.250	89	82	99	98	76	76	76	93	112	93	96	118	79	60	56	41
2.250	2.500	89	73	70	87	88	86	74	82	71	57	45	76	76	76	80	69
2.500	2.750	63	35	47	55	70	63	72	76	61	51	33	38	65	66	58	53
2.750	3.000	60	37	23	32	46	44	50	49	37	22	13	11	53	51	62	52
3.000	3.250	27	14	18	36	41	45	45	35	28	18	13	17	43	44	38	51
3.250	3.500	27	11	13	26	23	35	27	25	13	9	8	11	33	30	35	41
3.500	3.750	16	4	7	18	21	14	16	17	16	10	4	7	9	27	29	29
3.750	4.000	11	2	10	12	11	17	20	13	8	3	1	1	12	13	15	10
4.000	4.250	5	1	5	11	14	12	15	14	3	0	0	2	11	19	14	27
4.250	4.500	3	0	3	2	10	8	9	6	3	2	1	1	11	10	13	10
4.500	4.750	0	1	2	4	2	9	3	3	2	0	1	0	6	16	7	10
4.750	5.000	0	1	1	3	11	5	6	5	1	2	0	0	5	8	13	11
5.000	5.250	0	0	0	2	0	6	5	5	1	0	0	0	2	6	9	11
5.250	5.500	2	0	1	3	4	2	5	2	1	0	0	1	3	3	4	15
5.500	5.750	0	0	0	4	1	4	1	0	0	0	0	0	3	6	4	6
5.750	6.000	0	0	1	0	5	2	3	2	0	0	0	0	2	0	3	6
6.000	6.250	0	0	0	0	2	1	1	1	1	0	0	0	1	3	1	4
6.250	6.500	0	0	0	1	1	2	1	1	0	0	0	0	0	0	1	5
6.500	6.750	0	0	2	1	1	0	1	0	1	0	0	0	0	1	1	0
6.750	7.000	0	0	0	1	0	0	0	1	0	0	0	0	0	1	2	2

Table B4. Hourly Distribution of Transit/Auto Travel Time Ratio in Seattle with Parking Penalties

Band 2:	Seattle	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200
0.000	0.250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.250	0.500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.500	0.750	1	2	5	2	2	3	2	2	2	2	3	3	3	2	2	2
0.750	1.000	12	21	16	14	9	9	11	10	9	18	21	14	11	9	9	5
1.000	1.250	25	42	42	22	16	17	15	15	21	31	40	39	19	16	17	21
1.250	1.500	53	111	86	59	47	45	44	51	60	86	100	83	57	45	46	40
1.500	1.750	89	101	106	81	73	75	79	65	99	135	149	113	78	63	64	58
1.750	2.000	96	99	95	96	90	78	73	97	124	106	116	127	70	71	72	57
2.000	2.250	89	75	79	82	73	70	71	77	78	76	59	71	73	74	65	58
2.250	2.500	59	41	47	50	76	71	65	71	65	49	35	55	69	69	65	58
2.500	2.750	54	38	24	41	43	47	59	55	38	22	13	19	57	42	44	45
2.750	3.000	31	13	13	38	29	45	41	32	18	13	9	12	37	36	41	41
3.000	3.250	24	5	13	23	28	27	24	18	15	4	3	10	19	33	29	42
3.250	3.500	10	2	8	10	17	10	12	18	9	6	2	2	10	21	27	20
3.500	3.750	4	0	7	8	13	13	17	9	5	1	0	1	13	20	16	17
3.750	4.000	3	0	4	8	9	11	14	11	3	1	1	2	14	15	18	19
4.000	4.250	0	1	2	2	8	10	3	6	2	2	1	0	9	10	9	13
4.250	4.500	0	1	2	5	6	9	12	9	2	0	0	0	8	11	12	17
4.500	4.750	1	0	0	4	4	6	4	3	0	0	0	1	2	6	6	14
4.750	5.000	1	0	2	3	4	2	2	0	0	0	0	0	0	4	5	8
5.000	5.250	0	0	1	3	3	2	1	1	1	0	0	0	2	3	2	3
5.250	5.500	0	0	0	0	1	1	2	0	1	0	0	0	1	0	0	6
5.500	5.750	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1	2
5.750	6.000	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2
6.000	6.250	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	3
6.250	6.500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
6.500	6.750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.750	7.000	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0

APPENDIX C. TEMPORAL VARIATION OF TRAVEL DISTANCES BY TRANSIT AND AUTO

Travel distances between the same set of ODs vary at different times of the day. This resulted from traffic conditions and available transit services at different hours changing the routes with shortest travel times. Average travel distance of trips at each hour during the 16-hour period are plotted in appendix C.

Please be noted that temporal variations in travel distances are small in magnitude, and the vertical axes does not start with zero.

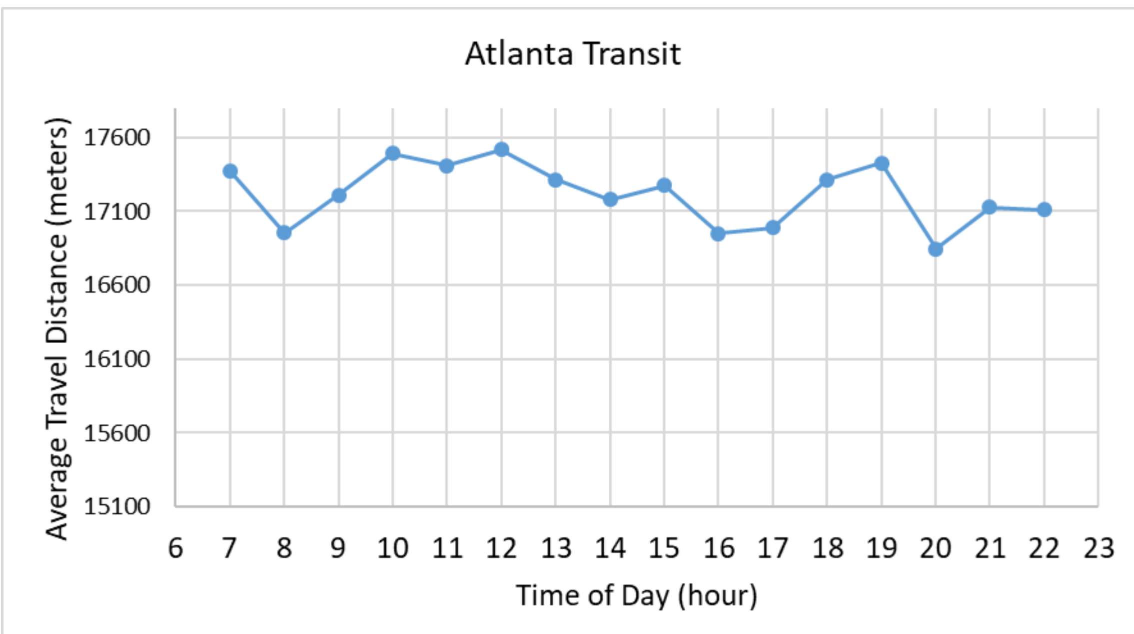

Figure C1. Temporal Variation of Travel Distances by Transit in Atlanta

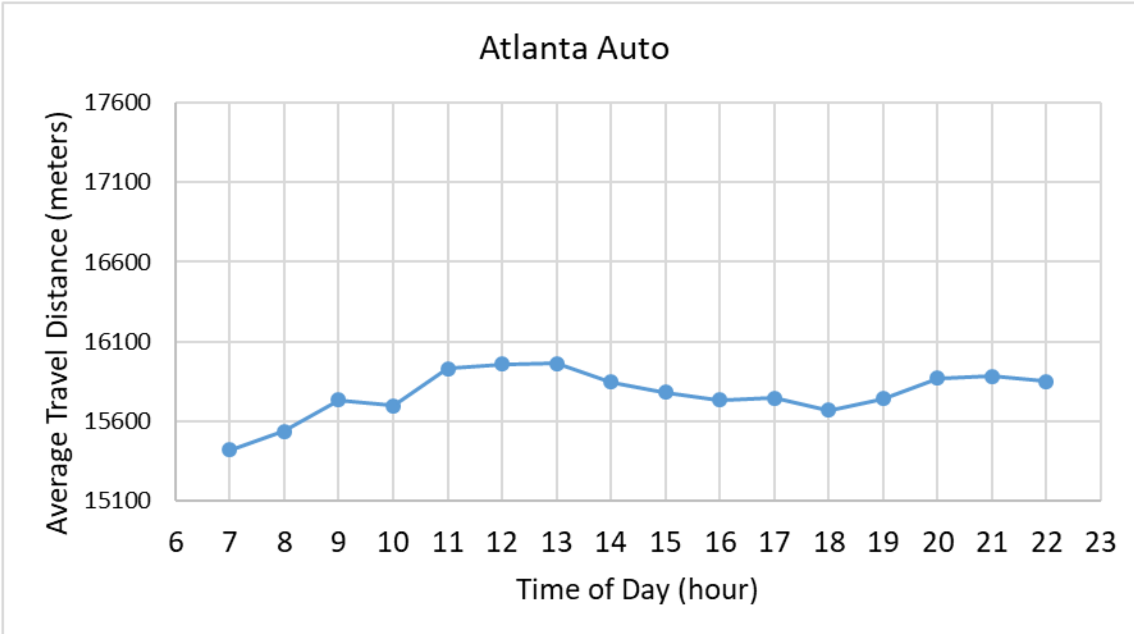

Figure C2. Temporal Variation of Travel Distances by Auto in Atlanta

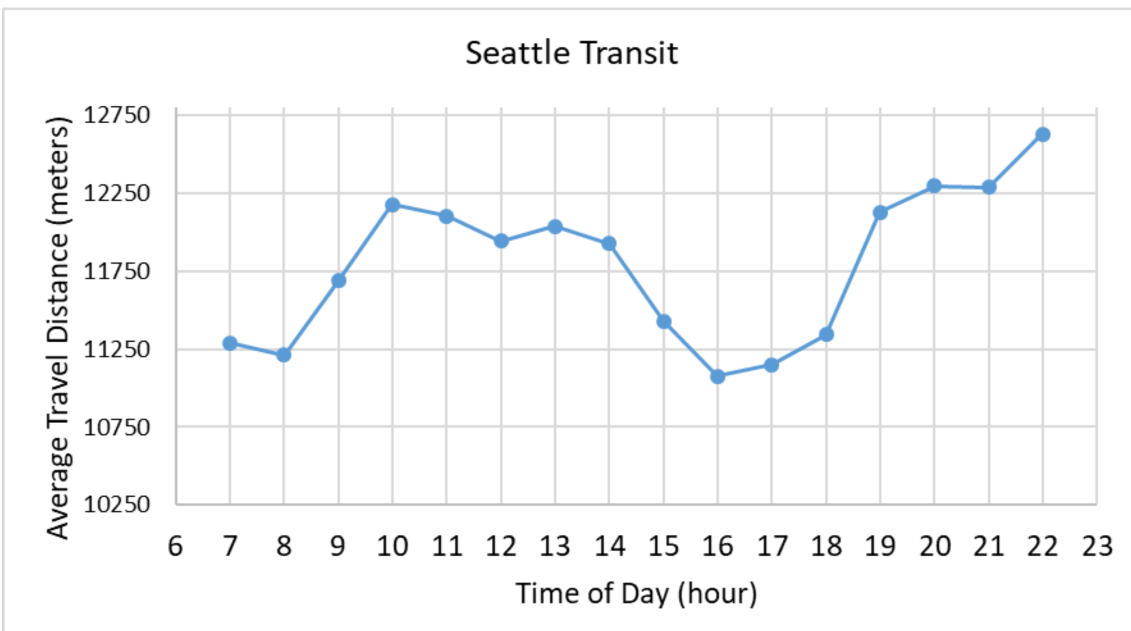

Figure C3. Temporal Variation of Travel Distances by Transit in Seattle

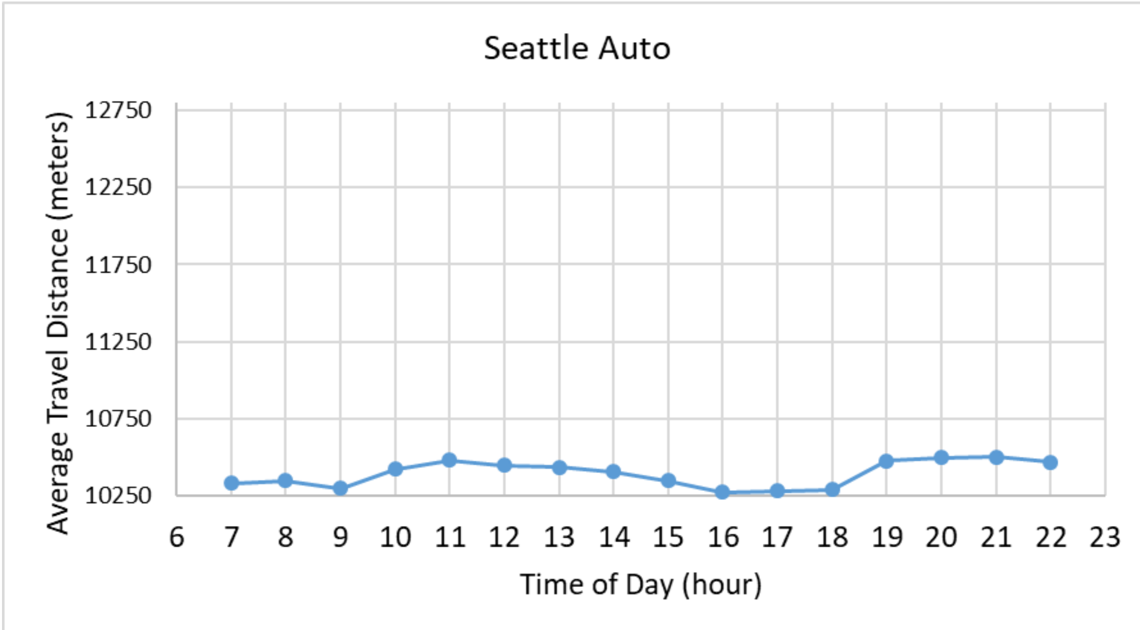

Figure C4. Temporal Variation of Travel Distances by Auto in Seattle

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